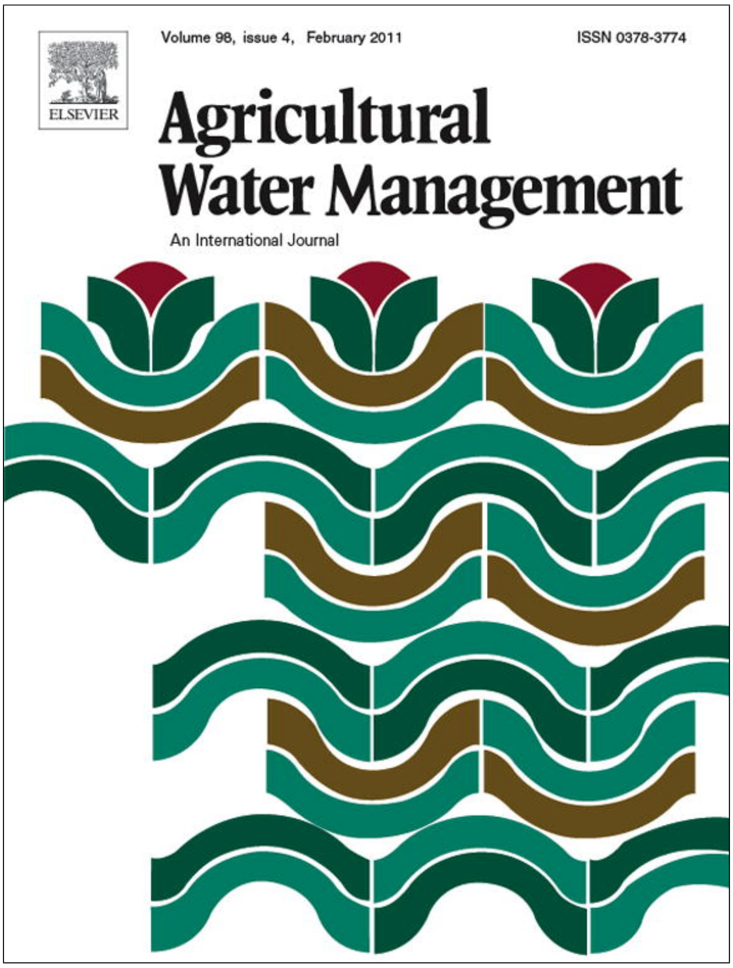
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Drought is a major yield loss factor for rainfed East African highland banana

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A B S T R A C T

Although drought stress has been identified among the production constraints of East African highland bananas (*Musa* spp., AAA-EA genome), no quantitative data were available to support this assumption. This study uses data from three on-station fertilizer trials (5–6 cycles) in Central and Southwest Uganda to quantify the effect of drought stress on banana production and explore possible interactions with nutrient availability. Production data were collected at individual plant basis from 1996 to 2002 in one trial and from 2004 to 2009 in two trials. Cumulative rainfall in the 12 months before harvest (CRF_{12}) was computed per plant from daily rainfall measurements. Average bunch weight ranged from 8.0 to 21.9 kg between trials and cycles and was 8–28% less in *dry* ($CRF_{12} \leq 905$ mm) than in *normal* ($905 < CRF_{12} \leq 1365$ mm) rainfall periods. Linear relations were observed between CRF_{12} and maximum bunch weight over the whole range of observed CRF_{12} (500–1750 mm), whereby every 100 mm decline in rainfall caused maximum bunch weight losses of 1.5–3.1 kg or 8–10%. Optimum annual rainfall for East African highland bananas may thus be well above 1200–1300 mm yr^{-1} as suggested earlier. Relative drought-induced yield losses were independent of soil fertility. Absolute losses on fertile/fertilized soils were similar to those recorded in well fertilized irrigation studies in Latin America. Our study suggests that drought-induced yield losses in areas of the East African highlands with annual rainfall < 1100 mm are perhaps as high as 20–65% compared to the wetter areas in this region. To improve productivity of smallholder banana farmers in Africa, more attention should be given to research geared towards improved water/drought stress management.

1. Introduction

East African highland bananas (*Musa* spp., AAA-EA genome) are an important food and cash crop for more than 30 million people in the East African highlands (Karamura et al., 1998), whereby bananas contribute on average between 16 to 31% of total calorie intake (Abele et al., 2007). With average observed farmer yields being less than 30 t ha^{-1} $cycle^{-1}$ and maximum observed farmer yields exceeding 60 t ha^{-1} $cycle^{-1}$, the gap between attainable and actual yields is often large (Bouwmeester et al., 2009; Wairegi et al., 2010). Scientists and farmers variously attribute the observed gap to low soil fertility, pests and diseases, poor crop management and drought stress (e.g., Bekunda and Woomer, 1996; Gold et al., 1999; Bagamba, 2007). To guide efforts of research and development programs to improve banana production, it is essential to understand the importance of the various production constraints. Several studies (e.g., Bananuka et al., 1999; Speijer et al., 1999; Zake et al., 2000; Gold et al., 2004; Murekezi, 2005) attempted to quantify individual production constraints, but due to their limitations (few fields, single visits) only present a snapshot picture of reality, whereas production constraints may vary considerably in space and time and may interact (Fermont et al., 2009; Wairegi et al., 2010).

Having a shallow rooting system and a permanent green canopy, bananas are thought to require an abundant and constant supply of water for optimal production (Robinson, 1996). Consequently, more than two-thirds of the bananas grown world-wide for export are estimated to be irrigated (Carr, 2009). On the contrary, East African highland banana production is completely rainfed. Rainfall in the major banana producing areas of this region has a bimodal pattern and averages 900–1100 mm yr^{-1} in much of Southwest Uganda, East Rwanda and the western Kagera region in Tanzania. The rainfall increases to above 1400 mm yr^{-1} in the high altitude areas close to the Albertine rift, Mt. Elgon, and some patches bordering Lake Victoria (Fig. 1). However, with a reported annual rainfall span of 600–2700 mm yr^{-1}, variation between years and sites is considerable (Bouwmeester et al., 2009). Hedge and Srinivas (1989) report estimates of evapotranspiration rates for banana ranging from 1200 to 2690 mm yr^{-1}, depending on climatic conditions and management. Purseglove (1985) and Robinson (1996) report similar values: a consumptive water use of 1300 mm yr^{-1} or 3–6 mm day^{-1} for optimal production. This is an indication that drought stress may limit banana production in large parts of East

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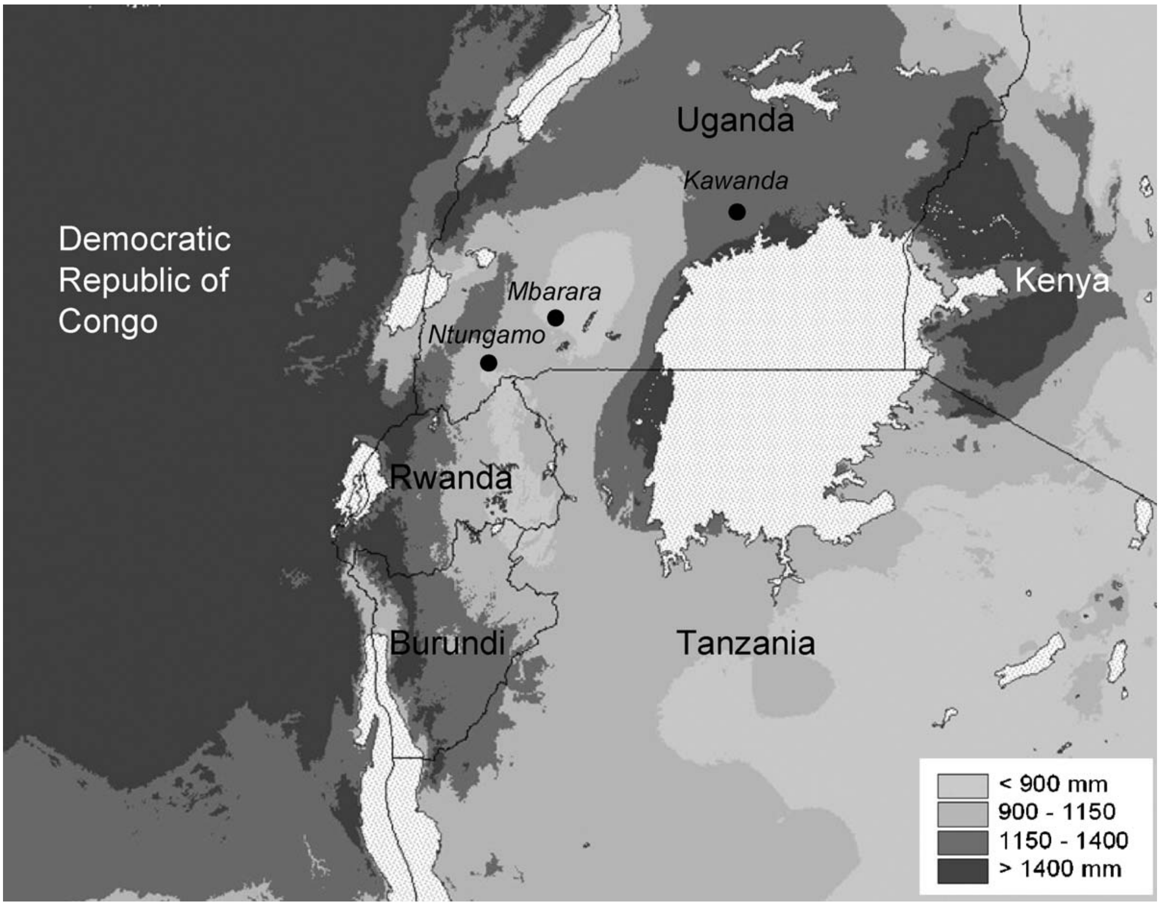

Fig. 1. Annual rainfall (mm) in the East African highlands. Circles indicate the location of the three research sites (Mbarara, Ntungamo and Kawanda). Data adapted from Hijmans et al. (2005).

Africa. Wairegi et al. (2010) found that drought stress was the primary yield constraint in a quarter of studied farmer fields in Southwest Uganda. Farmers in Rwanda, Burundi and Eastern DRC identified drought stress as the second most important constraint to production, following declining soil fertility (Murekezi and van Asten, 2008; Bouwmeester et al., 2009). Climate change, which is thought to affect rainfall distribution patterns and possibly will result in more intense dry spells in East Africa (Hulme et al., 2001), may further increase the impact of drought stress on banana production.

Under drought, roots produce signals that close stomata, allowing the banana to remain highly hydrated, but reducing carbon assimilation and therefore yield (Turner et al., 2007). Expanding tissues such as emerging leaves and growing fruits are among the first to be affected. Considerable research has been conducted in the broad field of banana irrigation (Robinson and Alberts, 1986). In contrast, little to no attention has been given to quantifying the effects of drought stress in rainfed banana systems.

East African highland bananas are generally cultivated on Ferralsols, Acrisols and Nitisols, though pockets of Andosols are found along the Albertine Rift (Zake et al., 2000). Foliar nutrient concentrations differ considerably between sites (CIALCA, 2008), indicating that nutrient stresses may be highly variable. Metcalfe and Elkins (1984) report that for most grain crops optimal fertilization decreases crop water requirements by 20%. Studies on the interactions between water and nutrient stresses for banana are scarce, though Baiyeri (1996) suggests that the use of N fertilization enhanced water use efficiency of plantain plants. However, Hedge and Srinivas (1989) found no significant interaction between N application rate and water use efficiency (WUE) in bananas. They explained that dry matter increase with N input increased in the same proportion as the water uptake, thus keeping WUE constant across N input rates. Lahav and Kalmar (1988) also reported that water use increased upon N application. Bhattacharyyaa and Madhava Raoa (1985) found that banana plants that received 10 t ha^{-1} of banana thrash mulch had an external WUE of 30–40% higher than plants without soil cover under different irrigation regimes. This may suggest a higher WUE for fertilized plants that produce more self-mulch and therefore produce a better soil cover. Cooper et al. (1987) showed that fertilizer application in barley under rainfed conditions resulted in large increases in WUE, but that this was only partially due to improved transpiration efficiency and largely due to reduced soil evaporation due to increased soil shading by the canopy.

We hypothesize that drought is an important production constraint to rainfed East African highland banana production. To investigate this hypothesis we analyzed data from three on-station trials (5–6 crop cycles) from Central and Southwest Uganda. Our specific objectives were (i) to quantify drought-induced yield losses of East African highland banana and (ii) to explore whether drought-induced yield losses are influenced by soil fertility status and fertilizer management.

2. Materials and methods

2.1. Experimental sites

Data from three medium-term fertilizer experiments (5–6 harvest cycles) were used to quantify the effect of cumulative rainfall on banana production in Uganda. The trials were installed in research farms in Mbarara (0°33′S, 30°36′E, 1380 masl) and Ntungamo (0°54′S, 30°15′E, 1405 masl) in Southwest Uganda, and in Kawanda (0°25′N, 32°31′E, 1156 masl) in Central Uganda (Fig. 1).

2.1.1. Climate

The climate at the three sites is typical for much of the banana growing areas in the mid-altitude East African highlands; mean daily minimum and maximum values range from 13 to 17 °C and 26 to 27 °C, respectively and temperatures are fairly constant throughout the year (Okech et al., 2004; Nyombi et al., 2010). Rainfall patterns are bimodal with dry spells from June to August and December to February (Fig. 2). Reference evapotranspiration at Kawanda for the period 1997–1999 averaged 3410 mm, as compared with a total rainfall of 2930 mm during this period (Ssali et al., 2003). Average annual rainfall during the trials was considerably lower in Mbarara and Ntungamo (1018 and 1019 mm, respectively) than in Kawanda (1310 mm; Table 1). Nonetheless, annual rainfall varied strongly between years in all sites. It ranged from 678 mm (1999) to 1230 mm (2000) in Mbarara, from 818 mm (2007) to 1319 mm (2006) in Ntungamo and from 1014 mm (2005) to 1460 mm (2007) in Kawanda (data not shown). CRF_{12} varied significantly between cycles in all sites ($P < 0.001$) and ranged from 767 mm for cycle 3 in Mbarara to 1538 mm for cycle 3 in Kawanda (Table 2). In all sites, less than 10 extreme rainfall events (>50 mm in 24 h) were recorded during the duration of the trials. The Mbarara trial experienced more pronounced drought periods than the Ntungamo and Kawanda trials: 31% of the trial duration could be considered as *dry* ($CRF_{12} < 905$ mm), whereas 19% could be considered as *very dry* ($CRF_{12} < 693$ mm). Lowest CRF_{12} values during the trial duration in Ntungamo and Kawanda were 770 and 920 mm, respectively. In Ntungamo, rainfall decreased average daily temperature by 0.5 °C on days without rain compared to days with rainfall.

2.1.2. Soils

Slopes at all sites are gentle to moderate (4–15%) and soils are classified as Ferralsols. (Nyombi et al., 2010; Okech et al., 2004). Soil fertility varied between trials (Table 1). Soils in Kawanda had the highest clay content (36%) and were generally the most fertile, with an average organic matter content of 3.3 g kg^{-1}, an average pH of 5.6 and moderate levels of exchangeable K (0.53 $cmol_+ \, kg^{-1}$). Soils in Ntungamo contained less clay (19%) and were generally the least fertile, with low levels of organic matter (0.6 g kg^{-1}) and exchangeable K (0.14 $cmol_+ \, kg^{-1}$). Soils in Mbarara were more acidic (pH of 4.3), but contained higher amounts of extractable P (5.2 mg kg^{-1}) compared to Kawanda (2.5 mg kg^{-1}) and Ntungamo (2.3 mg kg^{-1}) and moderate levels of exchangeable K (0.50 $cmol_+ \, kg^{-1}$). All trials showed strong variation in soil fertility parameters between blocks and plots, often – but not always – following the slope. This was most apparent from the

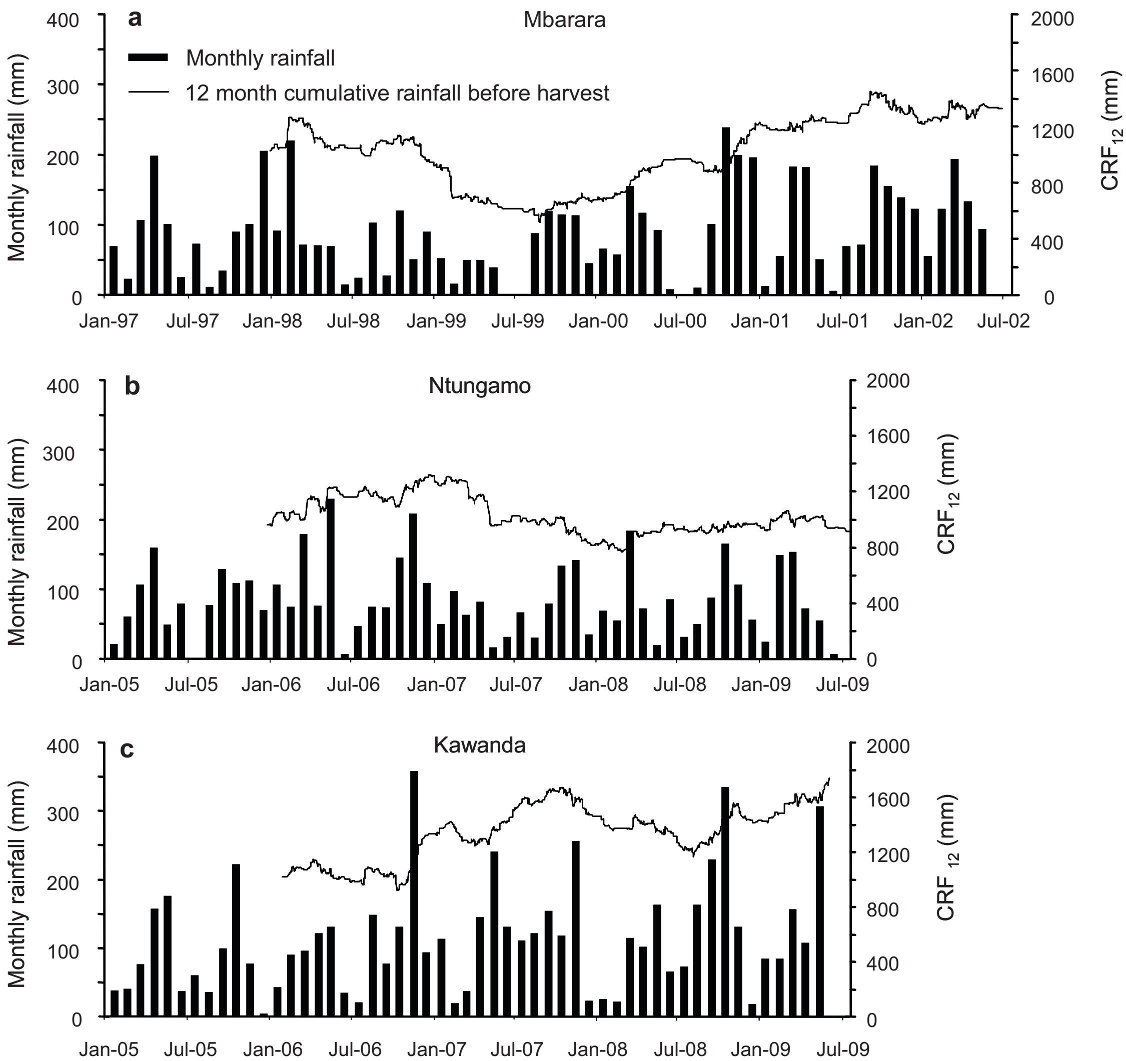

Fig. 2. Monthly rainfall and 12 months cumulative rainfall before harvest (CRF_{12}) from January 1997 to June 2002 in the Mbarara trial (a), from January 2005 to July 2009 in the Ntungamo trial (b) and from January 2005 to May 2009 in the Kawanda trial (c).

Table 1
Main soil characteristics and annual rainfall for the 1997–2002 Mbarara trial, the 2005–2009 Ntungamo trial and the 2005–2009 Kawanda trial.

	Soil characteristics						Rainfall (mm yr^{-1})
	pH water (1:2.5)	OM (%)	Tot N (g kg^{-1})	Ext. P (mg kg^{-1})	Exch. K ($cmol_+$ kg^{-1})	Clay (%)	
Mbarara	4.3	2.5	0.14	5.2	0.50	19	1019
Ntungamo	4.9	0.6	0.09	2.5	0.14	23	1018
Kawanda	5.6	3.3	0.13	2.3	0.53	36	1310

Table 2
12 months cumulative rainfall before harvest (CRF_{12}), fresh bunch weight (ABW) and time between two consecutive harvests (H-H) of AAA-EA banana for cycles 2–6 in the 1997–2002 Mbarara trial, the 2005–2009 Ntungamo trial and the 2005–2009 Kawanda trial by cycle and K fertilization[a].

	Mbarara				Ntungamo				Kawanda			
	n	CRF_{12} (mm)	ABW (kg)	*H–H* (days)	*n*	CRF_{12} (mm)	ABW (kg)	*H–H* (days)	*n*	CRF_{12} (mm)	ABW (kg)	*H–H* (days)
Cycle												
2	257	998	14.4	285	213	986	16.6	242	264	1189	10.5	229
3	140	767	8.4	323	150	900	19.3	284	271	1538	13.2	275
4	247	1065	11.4	334	46	962	20.9	281	251	1351	13.1	259
5	313	1289	15.2	290	23	987	21.9	275	119	1476	11.6	268
6	161	1295	21.1	264	–	–	–	–	–	–	–	–
K Fert												
No	526	1109	12.0	300	122	951	7.2	262	425	1365	10.6	259
Yes	593	1106	16.0	286	310	954	22.6	264	480	1387	13.6	255
Average	1118	1108	14.2	292	432	953	14.9[b]	263	905	1376	12.1	257
P for the effect of:												
Cycle	<0.001	<0.001	<0.001		<0.001	<0.01	<0.001		<0.001	<0.001	<0.001	
K Fert	ns	<0.001	<0.01		ns	<0.001	ns		ns	<0.001	ns	

[a] No K fertilization consisted of 0-0-0 kg ha^{-1} NPK in the Mbarara trial and 0-0-0 or 400-50-0 kg ha^{-1} NPK in the Ntungamo and Kawanda trials; K Fertilization consisted of 100-50-100 kg ha^{-1} NPK in the Mbarara trial and 150-50-600 or 400-50-600 kg ha^{-1} NPK in the Ntungamo and Kawanda trials.
[b] Non-weighted average to avoid bias towards fertilized plants.

exchangeable K values that ranged between blocks from 0.33 to 0.63 $cmol_+$ kg^{-1} in Mbarara, from 0.12 to 0.18 $cmol_+$ kg^{-1} in Ntungamo, and from 0.39 to 0.68 $cmol_+$ kg^{-1} in Kawanda (data not shown). Additional information on the trials and their sites can be found in Nyombi et al. (2010) and Okech et al. (2004).

2.1.3. *Trial setup and management*

In all sites, pest-free tissue-cultured plants of popular East African highland cooking bananas were used. The cultivar *Enyeru* was used in Mbarara, while the cultivar *Kisansa* was used in Ntungamo and Kawanda. Both trials were planted at 3 m × 3 m spacing, resulting in a plant density of 1111 mats ha^{-1}. Excess suckers were removed to maintain mat densities over time. Dead leaves and remaining above-ground biomass after harvest (i.e. leaves, corm and pseudostem) were chopped and spread as surface mulch.

The Mbarara trial (Trial 1) was planted on fallow land in October 1996. The first bunches were harvested in January 1998 and data collection lasted up to June 2002, covering 5–6 crop cycles. The trial was installed to study the effect of inorganic fertilizer and weevil (*Cosmopolites sordidus* Germar) control on crop performance (Okech et al., 2004). Weevil damage was low and control measures had no significant effect. We therefore only consider fertilizer application in this paper; a control without fertilizer versus 100-50-100 kg ha^{-1} yr^{-1} N-P-K. A randomized complete block design (RCBD) with four replications was used, whereby blocks followed the contour lines. Each plot consisted of 7 × 7 mats and plots were separated by 20-m wide grass strips to minimize fertilizer run-off/run-on effects. Nitrogen was applied as Urea in a 4-split application during the year, potassium was applied as muriate of potash (MOP) in a 2-split application, whereas phosphorus was applied as triple superphosphate (TSP) once per year.

The Ntungamo and Kawanda trials (Trials 2 and 3, respectively) were planted in October to December 2004 on fields with no recent banana history. First bunches were harvested in February and March 2006, while data collection lasted up to May and July 2009 for Kawanda and Ntungamo, respectively, covering 3–5 crop cycles. The trials were installed to study the effect of N, P, K, micro-nutrients and weevil-control on crop performance. Crop response to fertilizer inputs in these trials were reported in Okech et al. (2004) for the Mbarara trial and Nyombi et al. (2010) for the Ntungamo and Kawanda trials. In Ntungamo, the use of N, P, K and micro-nutrients significantly increased banana bunch weight, whereas weevil control did not, but K had by far the largest impact on bunch weight (data not shown). In Kawanda, K significantly increased bunch weight, whereas the other factors did not have an effect on bunch weight (data not shown). For this paper, we therefore used six treatments with contrasting K fertilizer use in the data analysis. The three treatments without K included: (T1) 0-0-0 kg ha^{-1} yr^{-1} N-P-K, no micronutrients, no weevil control; (T2) as T1 but with weevil control and (T3) 400-50-0 kg ha^{-1} yr^{-1} N-P-K, with micronutrients and weevil control. The three treatments with full K application (600 kg ha^{-1} yr^{-1}) included (T4) 150-50-600 kg ha^{-1} yr^{-1} N-P-K, with micronutrients and weevil control; (T5) as T4 but with 400 kg ha^{-1} yr^{-1} N and (T6) as T5 but without weevil control. Plots with weevil control were included to increase the number of observations available for further analysis. Micronutrient application consisted of 60, 6, 0.6 and 1 kg ha^{-1} yr^{-1} Mg, Zn, Mo and B, respectively, whereas weevil control was done with Dursban (active ingredient chlorpyrifos). A RCBD design with four repetitions was used, whereby blocks followed the contour lines and each plot consisted of 5 × 7 mats. Nitrogen was applied as Urea, potassium as MOP, phosphorus as TSP and micro-nutrients as sodium molybdate, borax, zinc sulphate and magnesium sulphate. N and K were applied in a 8-split application (4 times per rainy season), while P and the micro-nutrients were applied in a 2-split application (start of each rainy season). Microbunds were installed between plots to prevent runoff/run-on. More details on management can be found in Nyombi et al. (2010).

2.1.4. *Banana production*

Complete data records were available for 59, 34 and 63% of the observed plants in Mbarara, Ntungamo and Kawanda, respectively.

Strong winds caused considerable toppling of plants in all trials, while many mats had not yet completed cycle 6 in Mbarara, cycle 5 in Kawanda and cycle 4 and 5 in Ntungamo by the end of data collection. Average fresh bunch weight ranged from 12.1 kg in Kawanda to 14.2 kg in Mbarara and 14.9 kg in Ntungamo and from 8.4 to 21.9 kg between sites and cycles ($P < 0.001$; Table 2). In all sites, fresh bunch weight was significantly ($P < 0.01$) influenced by cycle. The number of fingers per bunch varied from 96 in Kawanda to 109 in Ntungamo ($P < 0.001$), whereas average finger weight ranged from 113 g in Ntungamo to 115 g in Kawanda (data not shown). The average time between two consecutive harvests within the same mat varied from 292 days in Mbarara to 263 and 257 days in Ntungamo and Kawanda, respectively ($P < 0.001$) and varied significantly between cycles ($P < 0.001$) in all sites (Table 2).

2.2. *Data collection and analysis*

The inner twenty-five mats in each plot of the Mbarara trial and inner fifteen mats in each plot of the Ntungamo and Kawanda trials were monitored on an individual basis. Flowering and harvesting date were recorded for each plant. Banana bunches were completely removed at horticultural maturity (i.e. just before ripening). In all trials, fresh bunch weight (fingers plus peduncle, with peduncle cut-off point where it crosses the petiole bases of the two last fully emerged leaves) was recorded in the field. In the Ntungamo and Kawanda trials, fresh finger weight and the number of fingers per bunch were also recorded at harvest time. Broken, toppled, or stunted plants, plants without a bunch, and plants with incomplete data records were excluded from the analysis. The absolute fresh bunch weight (ABW) was used to calculate the relative bunch weight (RBW) as the ratio of the ABW to the 95 upper percentile ABW. The RBW was calculated to study the relative yield decrease as a function of drought and nutrient stresses. The time between two consecutive harvests (H-H) was calculated from the harvest dates of bunches of consecutive cycles within the same mat.

Rainfall data were collected daily using a rain gauge in each site. The cumulative rainfall in the 6, 9, 12 and 15 months prior to the date of harvest (CRF_6, CRF_9, CRF_{12} and CRF_{15}) and in the 3, 6 and 9 months prior to the date of flowering ($CRFF_3$, $CRFF_6$ and $CRFF_9$) were computed for each bunch harvested. *Very dry*, *dry*, *normal* and *wet* periods were determined on the basis of the combined rainfall records, using 10, 20 and 80 percentile rainfall values (i.e. 693, 905 and 1365 mm) as lower cut-off points. Following Stroosnijder (2009), precipitation use efficiency (PUE) at crop level, expressed in $kg\,ha^{-1}\,mm^{-1}$, was calculated for each harvested bunch as:

$$PUE = \frac{Yield}{CRF_{12}} \quad (1)$$

whereby CRF_{12} is the cumulative rainfall in the 12 months prior to the date of harvest and Yield ($kg\,ha^{-1}\,yr^{-1}$) is calculated as:

$$Yield = \frac{365}{H-H} \times ABW \times Density \quad (2)$$

whereby *H–H* is the time in days between two consecutive harvests within the same mat, ABW is the absolute fresh bunch weight in kg and Density is the number of plants per hectare as used in the trials.

Composite soil samples were taken at planting; 4 sub-samples per plot at 0–15 cm depth in the Mbarara trial and 5 sub-samples per plot at 0–16 cm depth in the Ntungamo and Kawanda trials. Samples were oven-dried at 40–50 °C, ground to pass through a 2 mm sieve and analyzed for pH, organic matter, total N (Kjeldahl method), Available P (Mehlich-3) and Exchangeable K (ammonium-acetate extraction) following Okalebo et al. (2002). Soil texture was determined with the hydrometer method.

Table 3
Effect of rainfall[a] and K fertilizer[b] on absolute fresh bunch weight (ABW), # fingers per bunch and finger weight of AAA-EA banana for cycles 2–6 in the 1997–2002 Mbarara trial, the 2005–2009 Ntungamo trial and the 2005–2009 Kawanda trial.

Rainfall class	K Fert	Mbarara[c]			Ntungamo					Kawanda				
		n	Prod. (# $day^{-1}\,ha^{-1}$)	ABW (kg)	*n*	Prod (# $day^{-1}\,ha^{-1}$)	ABW (kg)	# fingers (–)	Finger weight (g)	*n*	Prod (# $day^{-1}\,ha^{-1}$)	ABW (kg)	# fingers (–)	Finger weight (g)
Very dry	No	37	0.7	9.3 ± 4.5	–	–	–	–	–	–	–	–	–	–
	Yes	54	1.0	11.5 ± 3.2	–	–	–	–	–	–	–	–	–	–
Dry	No	54	1.5	9.4 ± 4.5	22	0.8	4.4 ± 2.7	57 ± 19	111 ± 6	–	–	–	–	–
	Yes	55	1.5	11.6 ± 4.3	60	2.2	21.4 ± 8.4	115 ± 27	113 ± 8	–	–	–	–	–
Normal	No	413	2.7	12.4 ± 6.3	100	0.8	7.8 ± 4.5	76 ± 28	110 ± 6	206	3.2	9.8 ± 3.5	85 ± 22	107 ± 28
	Yes	455	2.9	16.9 ± 6.9	250	2.2	22.9 ± 7.1	125 ± 28	114 ± 15	195	3.0	12.6 ± 4.2	93 ± 25	124 ± 32
Wet	No	22	2.1	16.2 ± 7.8	–	–	–	–	–	219	2.2	11.3 ± 4.6	95 ± 27	106 ± 29
	Yes	29	2.8	19.2 ± 7.3	–	–	–	–	–	285	2.9	14.2 ± 5.2	107 ± 29	121 ± 40
P for the effect of:														
Rainfall class (R)				<0.001			<0.001	<0.001	ns			<0.001	<0.001	ns
K Fertilizer (K)				<0.001			<0.001	<0.001	<0.05			<0.001	<0.001	<0.001
R × K				ns			ns	ns	ns			ns	ns	ns

[a] Rainfall classes are defined using 10, 20 and 80 percentile values of the combined rainfall records. Periods that received less that 693 mm in the 12 months before harvesting were considered as 'Very dry', periods receiving between 693 and 905 mm were classified as 'Dry', periods receiving between 905 and 1365 mm were classified as 'Normal', while periods receiving more than 1365 mm were classified as 'Wet'.
[b] No K fertilization consisted of 0-0-0 $kg\,ha^{-1}$ NPK in the Mbarara trial and 0-0-0 or 400-50-0 $kg\,ha^{-1}$ NPK in the Ntungamo and Kawanda trials; K Fertilization consisted of 100-50-100 $kg\,ha^{-1}$ NPK in the Mbarara trial and 150-50-600 or 400-50-600 $kg\,ha^{-1}$ NPK in the Ntungamo and Kawanda trials.
[c] No data available on # fingers per bunch and finger weight.

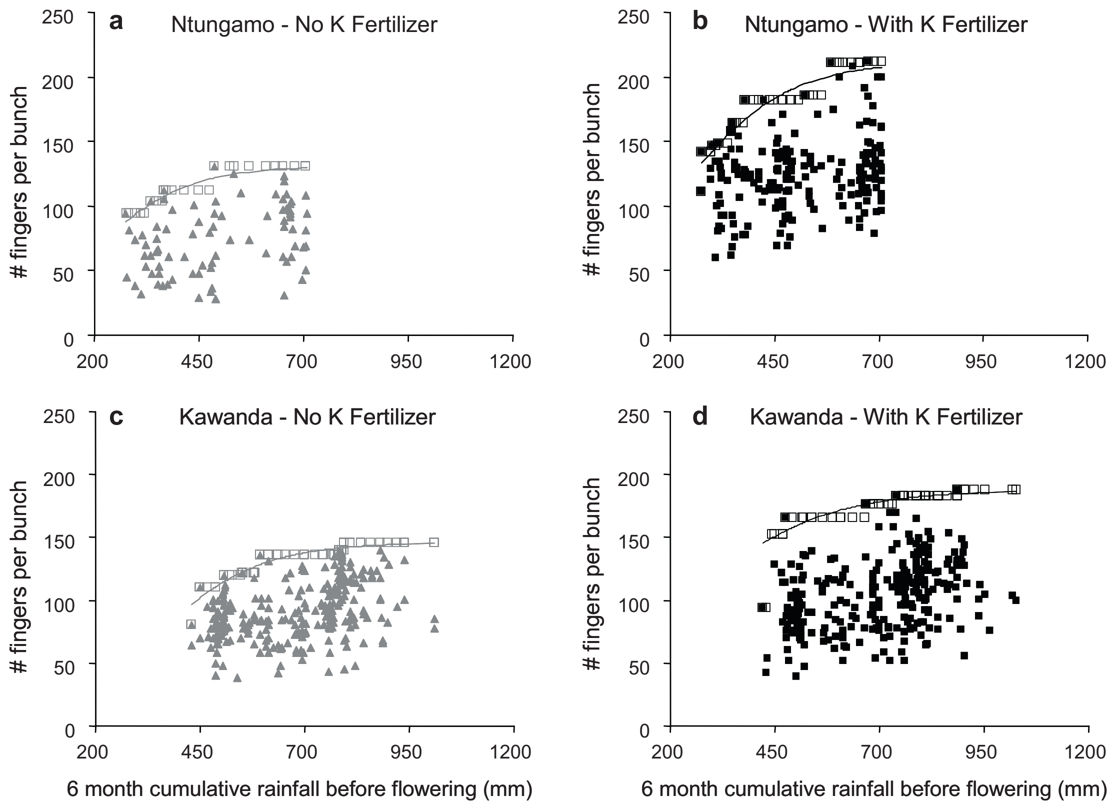

Fig. 3. Effect of 6 months cumulative rainfall before flowering ($CRFF_6$) on the number of fingers per bunch of AAA-EA banana's for all observations without K (a and c) and with K (b and d) fertilizer in the 2005–2009 Ntungamo trial (a and b) and the 2005–2009 Kawanda trial (c and d). Lines indicate boundary lines, open squares indicate boundary points. See text for further explanation.

2.3. Analytical approach

Analysis of variance was performed to test for the effect of cycle, K fertilization and/or rainfall on the absolute bunch weight, time between two consecutive harvests, number of fingers per bunch and average finger weight. Non-parametric tests for two or more independent samples using the Mann–Whitney U or Kruskal Wallis test, respectively, were performed if variables could not be normalized by transformation. Statistical analyses were carried out using SPSS for Windows (version 10.0).

The boundary line approach (Webb, 1972) was used to further detail the effect of cumulative rainfall on ABW and RBW for each trial. This approach has been used to determine yield functions in order to establish optimum soil and plant nutrient levels (e.g., Evanylo and Summer, 1987) or to rank crop growth constraints (e.g., Casanova et al., 1999; Fermont et al., 2009; Wairegi et al., 2010). Boundary lines are fitted regression lines through the upper points of a data cloud whereby ABW or RBW are fitted on the *Y*-axis and cumulative rainfall on the *X*-axis. It is assumed that the upper boundary points subsequently represent the maximum bunch weight that can be achieved at a given level of cumulative rainfall. Points that are below the boundary line are assumed to experience other crop growth constraints. Boundary points through which regression lines were fitted were selected using the algorithm (BOLIDES) developed by Schnug et al. (1996). Pearson correlations of ABW with CRF_6, CRF_9, CRF_{12} and CRF_{15} were calculated for all trials. ABW was most consistently and positively associated with CRF_{12}. Therefore, for each block (4) and K fertilizer level (without/with) in the three trials, boundary lines were defined that described the relation between CRF_{12} and maximum ABW and RBW. Maximum bunch weights did not approach a clear plateau value within the range of rainfall observations in the large majority of cases; i.e. it could normally be expected that bunch weights no longer increase ones a certain minimum rainfall threshold is achieved. Hence, linear functions and not S-type curves (e.g., Fermont et al., 2009) were fitted through the boundary points. Bunch weight observations below the boundary line suggest that constraints other than rainfall (i.e. CRF_{12}) contribute to limiting plant production. Within each trial, we tested for each block whether K fertilization affected the gradients of the boundary lines using simple linear regression with groups function within GenStat Discovery version 3.0.

For each trial, the mean relation between CRF_{12} and maximum ABW (RBW) was determined by averaging all available boundary points for each step of 20 mm CRF_{12}. Separate relations were determined for the two K fertilizer treatments (with and without). Two-way Anova was applied using GenStat (Payne et al., 2003) to compare if ABW and RBW boundary line gradients varied between trial sites and fertilizer treatments.

In newly planted banana fields in the East African highlands, production generally increases during the first few cycles due to the build-up of biomass and subsequent transfer of resources from mother plant to follower suckers (e.g., Nyombi et al., 2010), which gives the suckers a better start during early growth. As cycle 1 bunch weights were significantly ($P < 0.001$) lower than the overall average, cycle 1 data were omitted from the analyses of the effect of rainfall on banana production.

3. Results

3.1. Effect of rainfall and K fertilization on banana production

3.1.1. Number of bunches harvested

With 1.5 bunches being harvested per day per hectare during *dry* periods (CRF_{12} between 693 and 905 mm) versus 2.8 bunches day^{-1} ha^{-1} during *normal* rainfall periods (CRF_{12}

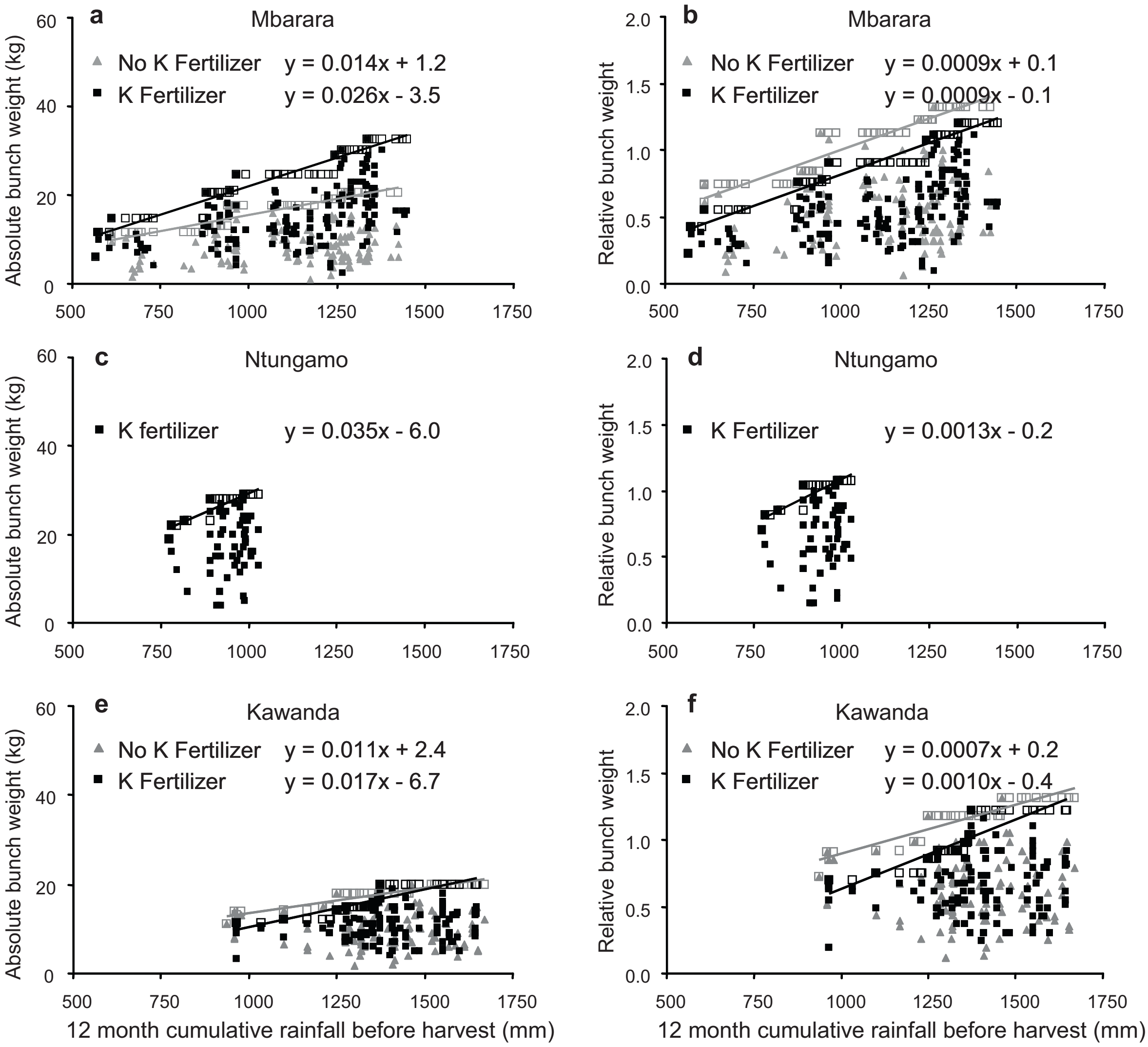

Fig. 4. Effect of 12 months cumulative rainfall before harvest (CRF_{12}) and K fertilization on absolute (a, c, e) and relative (b, d, f) bunch weight of AAA-EA banana for cycle 2–6 in block 3 of the 1997–2002 Mbarara trial (a and b), the 2005–2009 Ntungamo trial (c and d) and the 2005–2009 Kawanda trial (e and f). Lines indicate boundary lines, squares indicate boundary points. See text for further explanation.

between 905 and 1365 mm), the Mbarara trial produced 46% less bunches in *dry* than in *normal* rainfall periods (Table 3). In *very dry* periods (CRF_{12} < 693 mm) bunch production was further reduced to 0.7 bunch day^{-1} ha^{-1}, or a loss of 71% compared to *normal* rainfall periods. In Ntungamo, dry weather conditions did not affect the number of bunches harvested, but absence of K fertilizer resulted in 61% less bunches (Table 2).

3.1.2. *Bunch components*

Drought stress significantly ($P < 0.001$) affected absolute bunch weight and the number of fingers per bunch, but not finger weight (Table 3). In *dry* periods banana bunches harvested in Ntungamo were on average 8% (1.5 kg) lighter and contained 10% fewer fingers than in a period with *normal* rainfall. Bunch weights in Mbarara decreased on average by 17% (3.1 kg) from *wet* to *normal* periods and by 28% (4.2 kg) from *normal* to *dry* periods, but did not further decrease in *very dry* periods. Bunch weights in Kawanda decreased on average by 13% (1.7 kg) from a *wet* to a *normal* period and contained 13% more fingers in a *wet* period. The number of fingers was positively associated with $CRFF_6$ in both the Ntungamo and the Kawanda trials (r = 0.24–0.36; $P < 0.01$; Fig. 3). S-shaped boundary lines, with plateaus starting between 650 and 800 mm, best described the maximum number of fingers obtained at each cumulative rainfall level. No consistent trends were found for the effect of drought stress on time from planting/emergence to flowering, time from planting/emergence to harvest and time between two consecutive harvests (data not shown).

K fertilization significantly ($P < 0.001$) increased average bunch weight by 214% (15.4 kg) in Ntungamo, by 33% (4.0 kg) in Mbarara and by 28% (3.0 kg) in Kawanda (Table 2). K fertilization also increased the number of fingers per bunch by 71% in Ntungamo and by 12% in Kawanda ($P < 0.001$) and individual finger weight by 4% in Ntungamo and by 15% in Kawanda ($P < 0.05$; Table 3). In Ntungamo, K fertilization reduced the time from planting/emergence to flowering and the time from planting/emergence to harvest by 44 and 34 days, respectively ($P < 0.01$; data not shown), but had no effect on time between two consecutive harvests (Table 2).

3.1.3. *Water-limited production*

In 20 out of 24 block × K Fertilizer combinations, CRF_{12} was positively and significantly ($P < 0.05$ in 12 cases) associated with ABW. Pearson correlations ranged from 0.11 to 0.58 in the Mbarara trial, from −0.06 to 0.43 in the Ntungamo trial and from −0.04 to 0.26 in the Kawanda trial. Boundary lines that describe the relation between maximum ABW and RBW were linear and pos-

Table 4
Effect of K Fertilizer[a] and K availability in the soil (0–16 cm) on the boundary line gradients[b] for absolute and relative bunch weight[c] versus 12 months cumulative rainfall before harvesting (CRF_{12}) of AAA-EA banana for cycles 2–6 in the 1997-2002 Mbarara trial, the 2005–2009 Ntungamo trial and the 2005–2009 Kawanda trial.

Block	K Fert	Mbarara				Ntungamo[d]				Kawanda			
		K soil ($cmol_+ kg^{-1}$)	*n*	ABW slope	RBW Slope	K soil ($cmol_+ kg^{-1}$)	*n*	ABW slope	RBW slope	K soil ($cmol_+ kg^{-1}$)	*n*	ABW slope	RBW slope
1	No	0.66	142	0.029a[e]	0.0010a					0.62	111	0.021a	0.0011a
	Yes	0.61	159	0.030a	0.0010a	0.19	88	0.021	0.0006	0.75	110	0.017a	0.0007b
2	No	0.47	134	0.020a	0.0011a					0.59	105	0.015a	0.0009a
	Yes	0.57	161	0.032b	0.0009a	0.05	80	0.026	0.0008	0.70	126	0.016a	0.0007a
3	No	0.31	132	0.014a	0.0009a					0.35	96	0.011a	0.0007a
	Yes	0.40	149	0.026b	0.0009a	0.13	60	0.035	0.0013	0.50	116	0.017b	0.0010b
4	No	0.41	118	0.015a	0.0008a					0.32	113	0.013a	0.0009a
	Yes	0.25	124	0.019b	0.0009a	0.13	82	0.029	0.0008	0.45	128	0.019b	0.0009a

[a] No K fertilization consisted of 0-0-0 kg ha^{-1} NPK in the Mbarara trial and 0-0-0 or 400-50-0 kg ha^{-1} NPK in the Ntungamo and Kawanda trials; K Fertilization consisted of 100-50-100 kg ha^{-1} NPK in the Mbarara trial and 150-50-600 or 400-50-600 kg ha^{-1} NPK in the Ntungamo and Kawanda trials.
[b] See text for more details.
[c] Relative bunch weight was defined for each observation as absolute bunch weight over 95% percentile value.
[d] Too few observations (14–49) were available for unfertilized conditions in Ntungamo to determine boundary lines.
[e] Numbers within same block followed by different letters are significantly different at $P < 0.05$.

itively related to CRF_{12} over the entire cumulative rainfall range (500–1750 mm) for all blocks and K treatments (Fig. 4). Gradients of the boundary lines describing the relation between maximum ABW and CRF_{12} varied from 0.011 to 0.029 kg mm^{-1} between blocks and trials if no K fertilizer was applied, and from 0.017 to 0.035 kg mm^{-1} with K fertilizer application (Table 4). Gradients of the boundary lines describing the relation between maximum RBW and CRF_{12} varied from 0.07 to 0.11% mm^{-1} between blocks and trials if no K fertilizer was applied, and from 0.07 to 0.13% mm^{-1} with K fertilizer application (Table 4). K fertilizer application significantly ($P < 0.05$) increased the gradients of the boundary lines for ABW observations in 5 out of 8 blocks, but did not affect the boundary lines for RBW observations in 6 out of 8 blocks (Table 4). K availability in the soil was positively associated with the gradients of the boundary lines for ABW in the Mbarara trial ($P < 0.05$), but not in the Ntungamo and Kawanda trials (data not shown).

Averaging the boundary lines per trial resulted in gradients of 0.015–0.022 kg mm^{-1} and 0.09–0.10% mm^{-1} between trials if no K fertilizer was applied, and gradients of 0.017–0.031 kg mm^{-1} and 0.08–0.09% mm^{-1} between trials with K fertilizer application for ABW and RBW, respectively (Fig. 5). Within locations, K fertilization affected neither the average gradients of the ABW nor the average gradients of the RBW boundary lines. The gradients of the average ABW boundary lines did vary between locations ($P < 0.05$), but the average gradients of the RBW boundary lines did not. The average gradient of the RBW boundary lines was 0.09% mm^{-1} for the

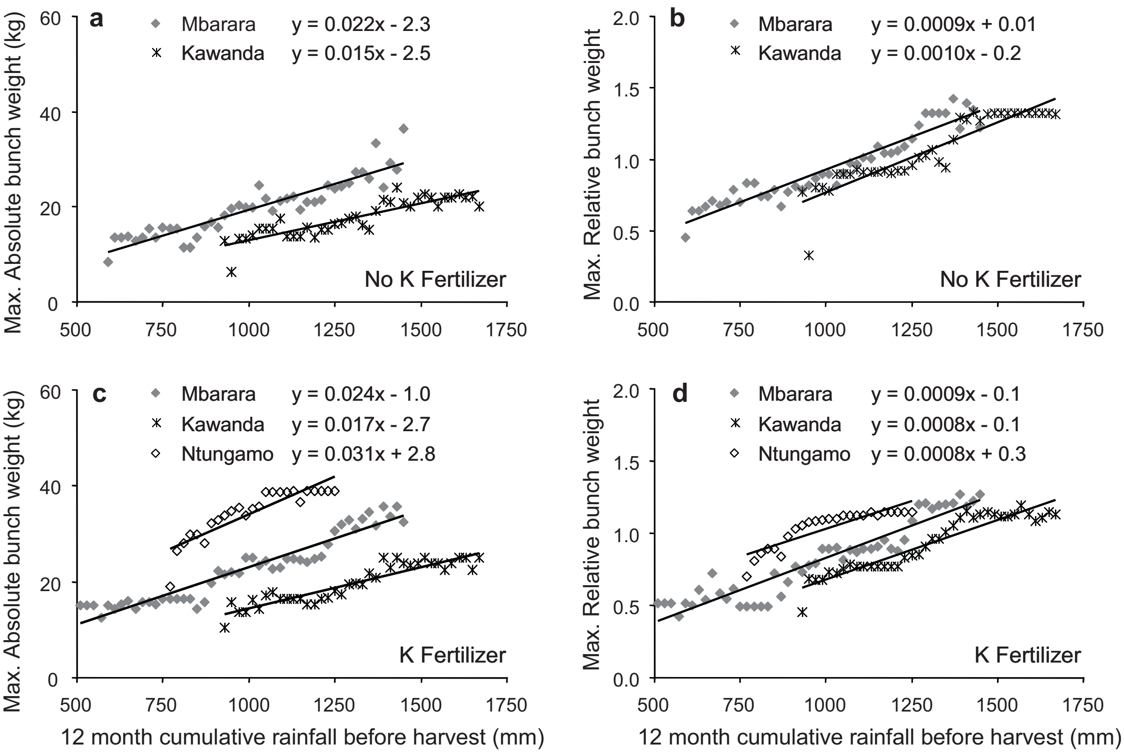

Fig. 5. Average relation between 12 months cumulative rainfall before harvest (CRF_{12}) and maximum absolute (a and c) and relative bunch weights (b and d) of AAA-EA banana without (a and b) and with (c and d) K fertilizer for the 1997–2002 Mbarara trial, the 2005–2009 Ntungamo trial and the 2005–2009 Kawanda trial. See text for further explanation.

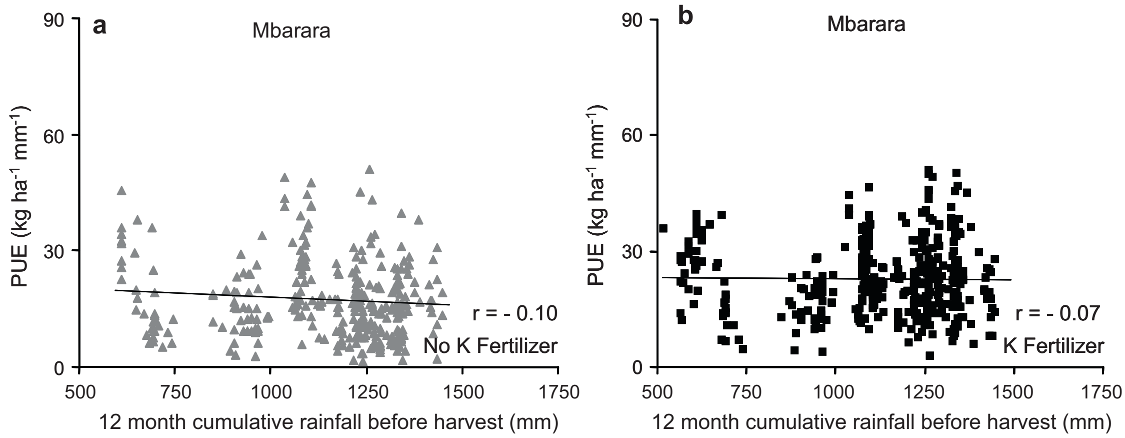

Fig. 6. Precipitation use efficiency (PUE) versus 12 months cumulative rainfall before harvest for observations with and without K fertilizer in the Mbarara trial. PUE was defined on individual plant basis.

entire data set. The factors site, fertilizer, and site × fertilizer had no significant ($P < 0.05$) impact on this gradient.

3.1.4. Precipitation use efficiency

Between sites, average PUE ranged from 13 to 17 kg ha^{-1} mm^{-1} for conditions without K fertilizer, and from 17 to 40 kg ha^{-1} mm^{-1} for conditions with K fertilizer (data not shown). PUE was independent of CRF_{12} (see Fig. 6).

4. Discussion

4.1. Variability in production

The observed range of average absolute bunch weights (8.4–21.9 kg; Table 2) would translate to average yields of 9–24 t ha^{-1} cycle^{-1}, if all mats had produced a bunch. These fall within the range of average farmer yields commonly reported in Uganda (Bagamba, 2007; Wairegi et al., 2010), but are lower than average farmer yields (18–63 t ha^{-1} cycle^{-1}) reported for other banana producing areas in the East African highlands (Bouwmeester et al., 2009), and are far below simulated potential yields of 100 t ha^{-1} cycle^{-1} for Uganda (Nyombi, 2010). Though annual rainfall was much higher in Kawanda than in Mbarara and Ntungamo (Table 1), absolute bunch weights in this site were lowest (Table 2). This may be related to a combination of relatively higher incidence of the fungal disease 'black sigatoka' and of high bulk densities (>1.5 g cm^{-3}) in the B-horizon (Nyombi, 2010). The latter would likely point to a limited exploration of the soil volume and restricted water and nutrient uptake, as banana roots are extremely sensitive to physical constraints (Delvaux, 1995).

4.2. Drought as a production constraint

The observed range in rainfall (Table 1) is representative for the banana producing areas in the central and eastern parts of the East African highlands and for dry to average years in areas located west of the Albertine Rift (Fig. 1). We used cumulative rainfall in the 12 months before harvest as an indicator of drought stress, as no data on available soil water were available. Runoff in our trials was low due to the use of contour bunds between plots. Leaching, however, may have been important after (rare) extreme rainfall events. Inherent to the bimodal rainfall distribution, banana production in our trials experienced two periods (1–3 months) of seasonal drought stress per year. Moreover, there is considerable variation in drought stress between years as shown from the large variation in CRF_{12} over time. As plantations in the East African highlands often persist for long periods of time (5–100 years; Wairegi et al., 2010), drought stress will affect all growth stages across all plantations.

Drought stress consistently reduced both average bunch weight and maximum (or water-limited) bunch weight in all trials (Table 3 and Fig. 5). Average bunch weight in *dry* periods ($CRF_{12} < 905$ mm) was 8–28% less than in *normal* rainfall periods ($905 \leq CRF_{12} < 1365$). Within the observed cumulative rainfall range (500–1750 mm), we found linear relations between rainfall and maximum bunch weights in all trials, whereby every 100 mm decline in rainfall resulted in an average 8–10% loss in relative maximum bunch weight or an average 1.5–3.1 kg loss in absolute maximum bunch weight (Fig. 5). Similar linear relationships between production and water use were found in irrigation experiments by Young et al. (1985) in Hawaii and by Goenaga and Irizarry (1995, 2000) in two contrasting conditions in Puerto Rico. Production in these trials was likely only water limited, as NPK fertilizer and chemical weed control were judiciously applied and pressure from pests and diseases was minimal. Young et al. (1985) observed that every 100 mm decline in evapotranspiration (E_t) resulted in a yield loss of 3.1 t ha^{-1} for the plant crop (*Musa* spp. AAA genome, cv. Cavendish) and a yield loss of 2.6 t ha^{-1} for the first ratoon. Data from Goenaga and Irizarry (1995, 2000) were used to calculate that every 100 mm decrease in irrigation water resulted in a 2.5–2.7 kg and a 2.4–3.1 kg loss in absolute bunch weight in their two trials using Cavendish cultivars as well. The similarity between these findings and absolute maximum bunch weight losses in our fertilized plots, suggest that the observed relation may be valid for fertile/well fertilized plots in a wider range of agro-ecologies and banana types. Although the drought studies on Cavendish and highland bananas are all on triploid acuminata cultivars, caution has to be taken when extrapolating results within the AAA genome group given the diversity that exists within this group. Ude et al. (2002) suggested that more than one M. acuminata subspecies may be involved in the origin of different triploid AAA bananas. There is some evidence that *Musa* cultivars containing a B genome are more drought tolerant (Thomas et al., 1998).

The observed linearity between cumulative rainfall and water-limited production within the observed cumulative rainfall range (500–1750 mm) suggests that, under the prevailing climatic conditions, East African highland bananas may have higher rainfall requirements than the 1200 mm yr^{-1} proposed by Doorenbos and Kassam (1979) for the humid tropics and the 1300 mm yr^{-1} proposed by Purseglove (1985) for bananas in general. This is confirmed by an irrigation experiment in Central Uganda, where maintaining soil moisture around field capacity through daily irrigation increased yields from 28 to 40 t ha in the plant crop and from 29 to 59 t ha in the first ratoon (Bananuka, 2001). Annual rainfall in this experiment ranged from 1490 to 1540 mm and evapotranspiration was larger than rainfall in 4–6 months per year. Indirect evidence that drought stress affects banana production in Uganda is provided by several mulch trials. Mulching is a common management strategy to increase water availability to the plant by promoting infiltration of rainwater and reducing evaporation (McIntyre et al., 2000). A mulching trial (4.5 years) in Central Uganda with an average rainfall of 1250 mm showed that a maize stover mulch plus a base fertilization of 0-50-60 kg ha^{-1} yr^{-1} NPK resulted in 20–50% higher banana yields than fertilization with 100-100-200 kg ha^{-1} yr^{-1} NPK only. This suggests that water availability limited production more than nutrients (Zake et al., 2000). A 13 months mulching trial with 1620 mm rainfall showed that a maize stover plus grass mulch increased banana yields from 5.2 to 14.1 t ha^{-1} yr^{-1} as a combined result of improved water uptake and higher nutrient availability (McIntyre et al., 2000).

4.3. Physiological effects of drought

Drought stress in our trials resulted in a reduction in finger numbers within a bunch, but had no effect on finger weight (Table 3). Drought stress may both negatively impact on fruit initiation (e.g., the number of hands and fingers) and on the fruit filling process (Robinson and Alberts, 1986). Its effect depends on the timing of the stress. Drought stress during flower initiation translates in a reduction in the number of hands/fingers (Holder and Gumbs, 1982, 1983), whereas drought stress after flower/bunch emergence translates in poor fruit filling (Mahouachi, 2007). If drought stress occurs during the whole growth cycle, then both the number of hands/fingers and fruit filling may be affected (Goenaga and Irizarry, 1995). In our trials, individual bunches were harvested throughout the year. It is therefore unlikely that drought stress occurred predominantly during flower initiation. Instead, the observed reduction in finger number, and not finger weight, may be explained by a possibly larger sensitivity of highland bananas to water stress at flower initiation than during fruit filling stage. Consequently, similar stress levels will reduce the number of fingers more than it will affect fruit weight (Holder and Gumbs, 1983; Robinson and Alberts, 1986). In our trials, the attainable number of fingers per bunch was reduced when cumulative rainfall in the 6 months before flowering was less than 550–700 mm (Fig. 3). During our trials, this was most likely for plants that flowered from September to November in Southwest Uganda, while in Central Uganda this was most likely for plants that flowered from May to August. Drought stress did not consistently affect time from planting/emergence to flowering or to harvesting nor did it consistently affect the time between two consecutive harvests in our trials. Many authors (Robinson and Alberts, 1986; Hedge and Srinivas, 1989; Goenaga and Irizarry, 1995, 2000) observed that irrigation advanced flowering and/or harvesting. The lack of consistent trends in our trials may be related to other factors (e.g., 'Sigatoka' and dense subsoil in Kawanda, K effects in Ntungamo) confounding possible effects of drought stress on banana development. It is unlikely that drought stress induced heat stress as average daily temperature was only 0.5 °C higher on non-rain days compared to rain days.

In long-term exploited plantations, annual production is determined by time between two consecutive harvests from the same mat (not time to flowering or harvesting), bunch weight and the number of productive mats. Drought-induced yield losses in rainfed East African highland banana production were the result of lower bunch weight (both average and maximum) as a result of less fingers per bunch in all sites, and through a loss in productive mats in one site (Tables 3 and 4, Fig. 5).

4.4. Influence of soil fertility status and fertilizer

In Ntungamo and Kawanda, K was the main limiting nutrient for banana production (Nyombi et al., 2010). K fertilization roughly increased banana yields by 30% in Mbarara and Kawanda and by more than 200% in Ntungamo (Table 2), where soil K was one-third of that in the other two sites (Table 1) and far below the critical level of 0.32–0.74 cmol+ kg^{-1} reported by Landon (1991). Lack of K decreased finger number as much or more as drought (Table 3) and in Ntungamo resulted in delayed flowering and harvesting. Bananas require large amounts of K as a harvest of 50 t ha^{-1} may remove 700–800 kg of K (Lahav, 1995). Soils in the Central and eastern part of the East African highlands consist mainly of highly weathered Ferralsols, Acrisols and Nitisols that have low inherent soil fertility (Sanchez et al., 1997). K limitations are therefore common in this region (Smithson et al., 2004).

The gradients of the boundary line functions that described the relation between maximum (or water-limited) ABW and CRF_{12} were generally steeper for K fertilized plots than for non-K fertilized plots (Table 4). In the Mbarara trial, boundary line gradients for ABW were positively associated with K availability in the soil. Hence, absolute maximum drought-induced yield losses are larger in sites with good soil fertility status or good soil fertility management than in areas with poor soil fertility status or no addition of nutrient inputs. Radersma et al. (2005) showed that low soil water content decreases nutrient diffusion and transport to the roots and thus hampers nutrient uptake. Consequently, root growth rates are slowed down, which further reduces nutrient uptake over time. Drought stress in the Ntungamo and Kawanda trials is therefore perhaps the main reason for the low apparent fertilizer recovery rates (<10% for N, <5% for P and 14–49% for K) as observed by Nyombi et al. (2010) during the first three cycles in these trials, compared to 15% N recovery observed by Prasertsak et al. (2001) and (75)% K recovery observed by Lopez and Espinosa (2000) in irrigated banana production. Haefele et al. (2006) also reported decreasing fertilizer use efficiencies with increasing drought stress in rainfed rice production. If, on the other hand, the impact of production constraints (e.g., nutrients, water) is reduced, this will result in more aboveground growth, increased evapotranspiration demands and consequently promote water absorption from the soil. Thus, the application of a mulch layer in Central Uganda resulted in greater water utilization at 0–30 and 30–50 cm depth (McIntyre et al., 2000). The application of K fertilizer in our trials considerably increased PUE, which was low (13–17 kg mm^{-1} in unfertilized and 17–40 kg mm^{-1} in fertilized plots) compared to water use efficiencies (37–76 kg mm^{-1}) in irrigated trials (Lahav and Kalmar, 1988; Hegde and Srinivas, 1991). The observation that PUE did not improve with increasing rainfall (Fig. 6), is perhaps an indication that introducing water conservation techniques, without simultaneously introducing better nutrient management, is unlikely to improve PUE.

In contrast to ABW, the relation between maximum or water-limited RBW and CRF_{12} was remarkably stable across a wide range of soil conditions and K fertilizer treatments; site, fertilizer, and site × fertilizer did not have any significant effect on these gradients. We observed an average relative bunch weight loss of 9% for every 100 mm decrease in rainfall across all sites (Table 4 and Fig. 5). This is an indication that relative drought induced yield losses are independent of plant nutritional status and suggests that the observed relation between CRF_{12} and maximum RBW may be extrapolated to areas with a similar ecology, but with a different soil fertility status or soil fertility management. Potential bunch weights in the drier parts (900–1100 mm yr^{-1}) of the East African highlands (e.g., Southwest Uganda, eastern Rwanda and Burundi and much of the Kagera region in Northwestern Tanzania) are therefore likely 20–65% lower than those in wetter parts (1350–1550 mm), such as Eastern DRC. This estimation is lower than the actual yield decline observed in farmers fields along the geographical gradient from Uganda to Rwanda/Burundi to eastern DRC: 9–24 t ha^{-1} $cycle^{-1}$ with 1000-1300 mm rainfall in Uganda, 18–45 t ha^{-1} $cycle^{-1}$ with 1000–1400 mm in Rwanda and Burundi and 35–63 t ha^{-1} $cycle^{-1}$ with 1350–1550 mm in eastern DRC (Bouwmeester et al., 2009; Wairegi et al., 2010). Actual yield differences between the regions may be larger due to (1) a loss in productive mats due to drought stress (Table 3); (2) reduced nutrient uptake under drought stress; (3) higher inherent levels of soil fertility in parts of eastern DRC and Rwanda (areas with soils on volcanic and relatively young metamorphic rock); and (4) different mat densities (CIALCA, 2008). Though irrigation, without doubt, has the potential to considerably increase banana production in the drier regions of the East African highlands, low farm-gate prices in areas that are located far (>150 km) from the major markets may be too low to justify such investments (e.g., Van Asten et al., 2008).

5. Conclusions

This study shows that drought-induced yield losses are important in rainfed East African highland banana production. Within the observed rainfall range (500–1750 mm) we found linear relations between CRF_{12} and maximum absolute and relative bunch weight in three trials across Central and Southwest Uganda, whereby a 100 mm decline in rainfall caused maximum (water-limited) bunch weight losses of 1.5–3.1 kg or 8–10%. Annual rainfall requirements for AAA-EA banana production may thus be well above 1200–1300 mm yr^{-1} as suggested earlier, though our results require confirmation in the form of irrigation experiments. Drought-induced yield losses in areas with a rainfall of less than 1100 mm yr^{-1} are estimated to be around 20–65% due to loss in bunch weight. Loss of productive mats due to drought stress will increase yield losses in many plantations. Relative bunch weight losses were independent of soil fertility and absolute losses on fertile/fertilized soils were similar to those recorded in well fertilized irrigation studies with Cavendish banana in Latin America. Although the results of our study correspond well with those found in other areas, further validation may be needed before our findings can be confidentially extrapolated across sites and cultivars.

Smallholder banana farmers in the East African highlands are unlikely to introduce irrigation practices on the short to medium term. Overcoming drought stress in these banana systems will therefore have to be attained through increasing rainwater use efficiencies. This may practically be achieved through a combination of mulching and fertilizer use, in combination with rainwater harvesting on steeper slopes and more drought resistant genotypes. In addition, farmers may be able to reduce the impact of drought stress on flowering by carefully managing sucker selection to avoid dry periods six months before flowering. Little to no research has been done on these themes in Africa. To overcome drought-induced yield losses and improve productivity of smallholder banana production in Africa, national and international agricultural research institutes will have to emphasize drought stress/water management on their research agenda.

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